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Sensitivity analysis on daylighting and energy performance of perimeter offices with automated shading

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ABSTRACT

This paper presents a comprehensive global uncertainty and sensitivity analysis of daylighting and energy performance for private offices with automated interior roller shades using an advanced integrated thermal and lighting simulation model. The purpose was to identify the more important factors with respect to building thermal and lighting energy performance so as to facilitate decision making in building design stage and simplify further investigation such as optimization analysis. Seven studied parameters were selected: window-to-floor ratio, shading transmittance, shading front and back reflectance, space aspect ratio, insulation thermal resistance and glazing type. The performance metrics include useful daylight illuminance (500–2000 lux), annual lighting, heating and cooling demand per unit floor area and annual source energy consumption per unit floor area. The uncertainty analysis is based on the Monte Carlo method with Latin Hypercube Sampling, showing the possible ranges in these performance indices. The sensitivity analysis uses a variance-based method in the extended FAST implementation. Application of the analysis to perimeter private office spaces for the climate of Philadelphia showed the first order and total order effects of each studied parameter to determine the building parameters that have the most significant impact. Results are presented for different facade orientations.

1. Introduction

Commercial buildings, primarily office buildings, consume a large amount of energy and present a rapid increase in total primary energy consumption. The situation of high energy requirements on one hand and limited energy resources on the other hand has sparked a lot of research activities concentrating on early stage building design as well as on retrofit efforts for energy saving purposes. Conventionally, previous studies used approaches based on evaluation of several alternative design options to identify the best solution [22] or analysis of influence coefficients in terms of a base case to determine the important design parameters [17,38]. In the design procedure, it is beneficial to identify the importance of design parameters correctly in order to efficiently develop design options or reach optimal design solutions. Recently, more advanced sensitivity analysis approaches have been employed in determination of the most important parameters in relation to building performance. Heiselberg et al. [12] used the elementary effects method to investigate which design parameters are the most important among the 21 selected factors to change in order to reduce the primary energy consumption. Their results showed that lighting control is one of the two most important parameters that will have the most significant effect. Mechri et al. [21] employed the Monte Carlo method with Latin Hypercube Sampling (MC-LHS) and the Analysis Of Variance-Fourier Amplitude Sensitivity Test method (ANOVA-FAST) for uncertainty and sensitivity analysis of heating and cooling energy needs. The first order effect of each studied factor was calculated and the envelope transparent surface ratio was distinguished as the most significant factor for both heating and cooling energy needs. In some studies [6,15,43,44], the MC-LHS method was also used to calculate the sensitivity indices such as the Standardized Regression Coefficient (SRC) and the Standardized Rank Regression Coefficient (SRRC) given that the model coefficient of determination is higher than 0.7 [32].

In the above mentioned studies, windows have gained enough importance as an influential envelope element. Usually one or more factors related to windows (including transparent surface ratio, *U*-value and solar heat gain coefficient) were considered in the analysis. However, those thermal parameters were considered only for the concern of heating/cooling load or energy consumption. A series of studies have focused on the glazing optical properties and the resulting effects on lighting, heating and cooling needs. It is well

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known that utilization of daylight in perimeter office spaces introduces opportunities for energy savings [7,18,29]. The daylighting performance is affected by many interfacing factors such as glazing size and properties, shading properties and control [3,25,35,39], room aspect ratio and orientation [8]. These factors also affect the thermal loads and hence the energy performance of space. In order to improve the overall performance via most effective approach in design, a sensitivity analysis should be applied to an integrated building model, especially when dynamic control of lighting systems or shading devices is in use. Furthermore, the different window properties are often correlated and therefore require great carefulness in defining the probability density functions and respective ranges. For example, a window with a high solar heat gain coefficient might also have a high *U*-value. Such properties are not completely independent and the combination between them is not really random.

This paper presents a comprehensive global uncertainty and sensitivity analysis of daylighting and energy performance for private offices with automated interior roller shades using an advanced transient simulation model. Studied performance indices include useful daylight illuminance, annual lighting, heating and cooling demand and annual source energy consumption. The uncertainty analysis is based on MC-LHS method showing the possible ranges in these performance indices. The sensitivity analysis uses a variance-based method in the extended FAST implementation. First order and total order effects of each studied parameter were calculated to determine the building parameters that have the most significant impact on the performance indices.

2. Uncertainty and sensitivity analysis

Mathematical methods for uncertainty and sensitivity analysis are well known [33,34]. In the past few decades, uncertainty and sensitivity analysis have become more and more popular in various engineering fields. In building physics practice, uncertainty analysis provides the expected distribution of possible values for a model response following the variations of the input parameters within their respective distributions and ranges. Building performance uncertainty may result from different groups of sources such as building material properties, design parameters and building functions. A realistic study should be performed with respect to a specific uncertainty type since it is difficult to combine them due to their different nature and significance on building performance [14]. Comparing the model response under uncertainty with monitored real data, uncertainty analysis is used to calibrate building models for better probabilistic predictions in retrofitting existing buildings [13,41]. Uncertainty analysis is also used to assess the feasibility of certain building techniques [27] given various building designs and usage. The top and bottom ranges of the model response usually indicates the necessity for a further sensitivity analysis and then influence the decision making at the building design stage.

The purpose of sensitivity analysis is to apportion the uncertainty in the model response to different sources of uncertainty in the model input. It distinguishes itself as a good practice by revealing which of the input parameters has a significant impact on the output so as to direct research priorities to factors that are responsible of the biggest output variability, and eventually achieve the design aim of energy saving or other purposes. There are many techniques that can be applied in uncertainty analysis. Among those, the Monte Carlo technique is the most popular one. It is based on performing multiple evaluations with randomly sampled points of model inputs according to their corresponding probability density functions, and then using the results of these evaluations to determine the uncertainty in model predictions. If the model is linear or at least monotonic to each of its inputs, these evaluations can also be used to determine the contributions of the inputs to this uncertainty by calculating SRC, SRRC or other indicators. In the meantime, several methods have also been developed for sensitivity analysis. For example, the differential method [19], Factorial method [10], Morris method [23] and variance-based methods are the often used approaches. The differential method is mostly used for local sensitivity analysis. The factorial method and the Morris method are usually employed to isolate the very few dominating factors among a large amount of inputs. In general, for a moderate number of factors (tens) and a model with short execution time (less than one minute), variance-based methods are ideal.

3. Methodology

3.1. Building simulation model

An integrated thermal and lighting building simulation model developed in a previous study [35,40] is used here with two improvements. The model has been validated with experimental measurements [36] and with EnergyPlus for simple facade configuration cases. Fig. 1 shows the flowchart diagram of the model. The model is composed of a daylighting calculation part and a thermal calculation part, which run simultaneously and are coupled by facade design parameters as well as by shading and lighting controls.

The lighting calculation includes four steps: calculation of incident illuminance on facade using the Perez model [28]; calculation of transmitted illuminance into space in terms of the angular glazing-shade system transmittance; calculation of interior surface luminous exitance and illuminance on work plane using the radiosity method [2,11]; and calculation of daylight metrics [24,30] and electric lighting requirements. In its previous version, the model simplified inter-reflections between the interior roller shade and the glazing interior surface. This may introduce small errors and reduce the importance of shade properties in the sensitivity analysis since the interior roller shade will affect the properties of glazing for both short-wave radiation and long-wave radiation. In this study, Eqs. (1)–(4) [9] are used in the current model to calculate some of the effective values of glazing and shading properties at each calculation time step (direct and diffuse components are separated appropriately):

$$\tau_{\mathrm{e}} = \tau_{\mathrm{g}} \cdot \frac{\tau_{\mathrm{sh}}}{1-\rho_{\mathrm{g}}^{\mathrm{b}} \cdot \rho_{\mathrm{sh}}^{\mathrm{f}}} \tag{1}$$

$$\alpha_{\mathrm{eg}}^{i,\mathrm{f}} = \alpha_{\mathrm{g}}^{i,\mathrm{f}} + \tau_{\mathrm{g}} \cdot \frac{\rho_{\mathrm{sh}}^{\mathrm{f}}}{1-\rho_{\mathrm{g}}^{\mathrm{b}} \cdot \rho_{\mathrm{sh}}^{\mathrm{f}}} \cdot \alpha_{\mathrm{g}}^{i,\mathrm{b}} \tag{2}$$

$$\alpha_{\mathrm{eg}}^{i,\mathrm{b}} = \frac{\tau_{\mathrm{sh}}}{1-\rho_{\mathrm{g}}^{\mathrm{b}} \cdot \rho_{\mathrm{sh}}^{\mathrm{f}}} \cdot \alpha_{\mathrm{g}}^{i,\mathrm{b}} \tag{3}$$

$$\alpha_{\mathrm{esh}} = \tau_{\mathrm{g}} \cdot \frac{\alpha_{\mathrm{sh}}}{1-\rho_{\mathrm{g}}^{\mathrm{b}} \cdot \rho_{\mathrm{sh}}^{\mathrm{f}}} \tag{4}$$

where τ_{e} is the effective system (including glazing and shading) transmittance; $\alpha_{\mathrm{eg}}^{i,\mathrm{f}}$ is the effective front glazing absorptance for the *i*th glass pane; $\alpha_{\mathrm{eg}}^{i,\mathrm{b}}$ is the effective back glazing absorptance for the *i*th glass pane; α_{esh} is effective shading absorptance; τ_{g} is glazing transmittance; $\rho_{\mathrm{g}}^{\mathrm{b}}$ is the back glazing reflectance; $\alpha_{\mathrm{g}}^{i,\mathrm{f}}$ is the front glazing absorptance for the *i*th glass pane; and $\alpha_{\mathrm{g}}^{i,\mathrm{b}}$ is the back glazing absorptance for the *i*th glass pane.

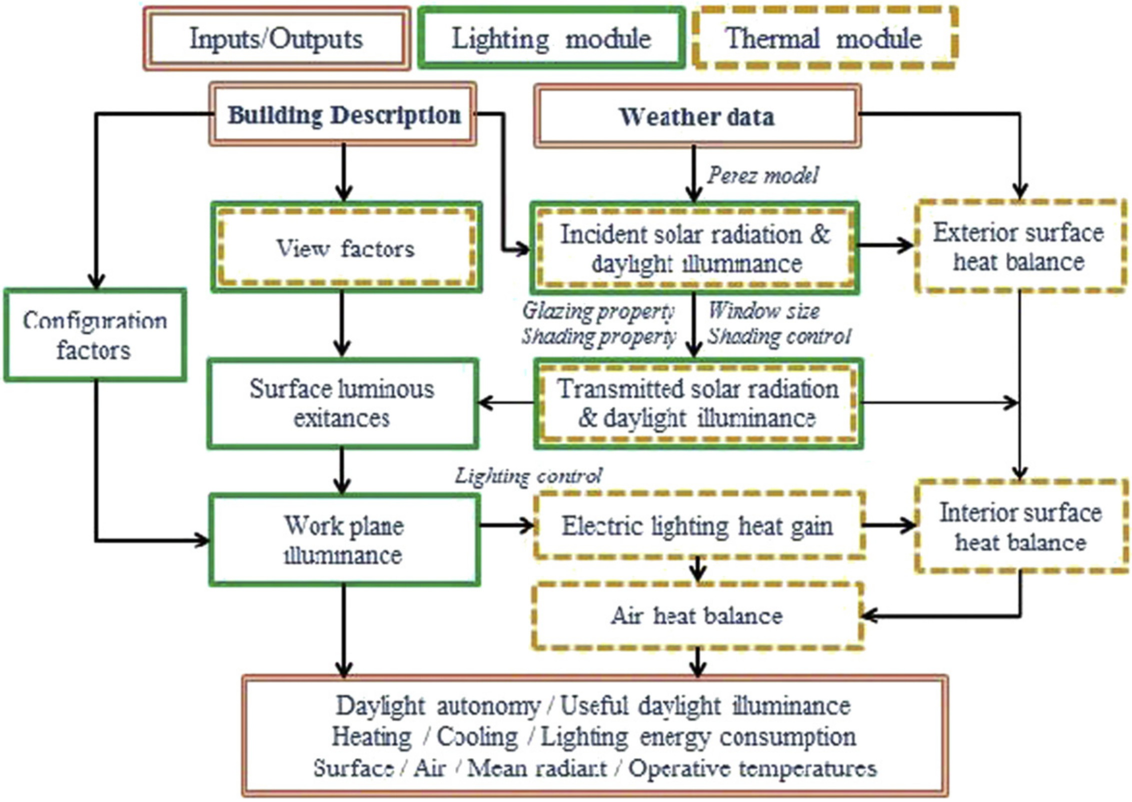

Fig. 1. Flowchart diagram for the integrated thermal and lighting building simulation model.

In the thermal calculations, the explicit finite difference thermal network approach is used to model the transient thermal response of the studied space. The current model tracks the percentage of the transmitted direct solar radiation falling on each surface. The transmitted diffuse solar radiation goes to each surface according to the respective area ratio. After the first absorption, the reflected part becomes diffuse radiation and is finally absorbed by each surface in terms of their respective area-absorptance weighting factors. Fig. 2 illustrates a schematic of the heat transfer mechanisms near a facade with a double-glazed window and an interior roller shade.

Every exterior surface receives solar radiation calculated as the product of surface absorptance and incident solar radiation calculated with the Perez model [28]; exchanges heat with the sky and the ground through radiation; exchanges heat with the outside air through convection; and conducts heat through the wall to the interior (or from the interior to the exterior in winter). The exterior surface convection heat transfer coefficients are calculated with DOE-2 convection model [9]. For interior surfaces, they receive transmitted solar radiation; receive radiative heat from internal equipment; exchange heat with other interior surfaces through radiation; exchange heat with indoor air via convection; and also exchange conductive heat within the wall. Radiation heat transfer between all surfaces is modeled in detail using radiosity method with non-linear heat transfer coefficients [37]. ASHRAE [1] correlations were used for the interior heat transfer coefficients. The opaque walls are discretized into two surface nodes and one mass node connecting with a capacitance (if the wall has a mass layer). The glazing system has one node for each of its glass panes. The interior roller shade has one node to represent the entire surface. An energy balance on each node is solved for every calculation time step using the following equation:

$$C_i \frac{T_{i,p+1} - T_{i,p}}{\Delta t} = \sum \left(\frac{T_{j,p} - T_{i,p}}{R_{ij,p}} \right) + S_{i,p} \tag{5}$$

where c_p is the specific heat, J/kg K; ρ is the density, kg/m^3; Vol is the volume of the mass node (i), m^3; T is temperature, °C; $p+1$ represents the next time step; Δt is the calculation time step, s; j represents all nodes connected to node i; R_{ij} is the total thermal resistance between nodes i and j, K/W, C_i is the capacitance of node (i), J/K m^2; and S_i is total heat input to node (i), W.

As shown in Fig. 2, the air in the gap between the glazing and the interior roller shade is also treated as a separate thermal node when the shade is closed. This node is considered to simulate the heat gain/loss from the gap to space air because of the difference between the zone air temperature and the gap air temperature. Given the zone air temperature, shading surface temperature, interior glass surface temperature and gap geometry, a pressure-balance equation can be used to determine gap air velocity, gap air mean equivalent temperature and gap outlet air temperature [9].

3.2. Uncertainty analysis

The Monte Carlo (MC) technique is used for uncertainty analysis in this study. One of the most important steps in MC analysis is the generation of a sample according to the distributions and ranges of studied factors. Various sampling procedures are available: random sampling, stratified sampling and quasi-random sampling. Latin Hypercube Sampling (LHS) is a particular case of stratified sampling. The range of each input factor is divided into l ($l > 2$) intervals of equal marginal probability, and within each interval one observation is made randomly. This sampling method has the advantage of representing all portions of a factor distribution by

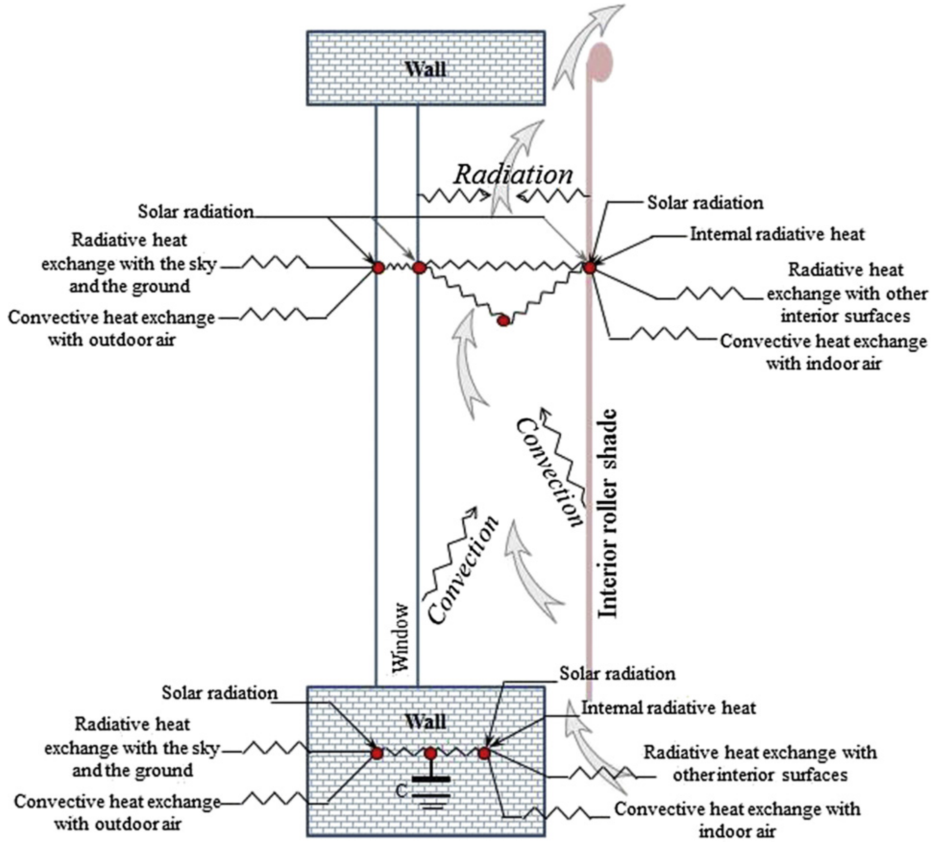

Fig. 2. Heat flows, solar gains and thermal nodes near a facade with a double-glazed window and an interior roller shade.

input values [20] and has been used in this study. The number of executions (n) is recommended as no less than 1.5 times of the number of factors (k) [16]. The uncertainty of the output may be represented with a frequency graph or histogram. The coefficient of variation (ν), which is the ratio of the standard deviation (σ) to the mean value (μ) given by Eqs. (6) and (7) is a good indicator to evaluate the dispersion of the outputs.

$$\mu = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{6}$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i-\mu)^2} \tag{7}$$

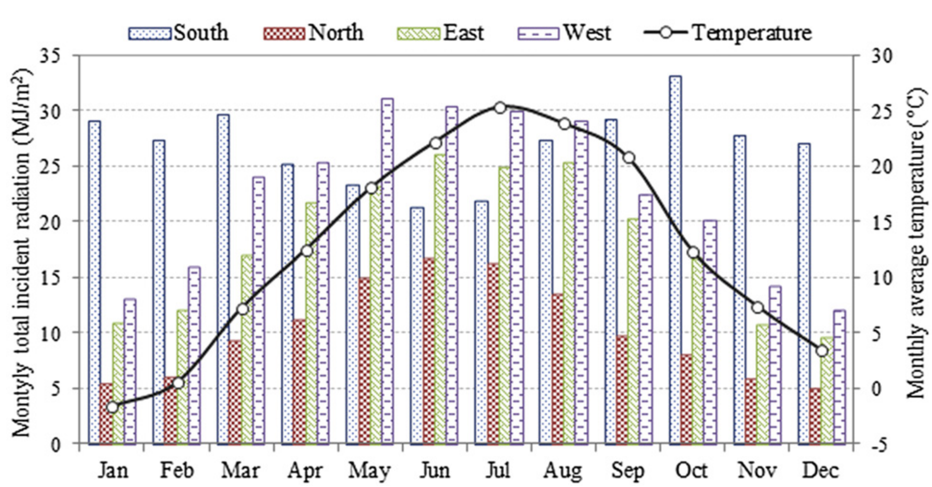

Fig. 3. Monthly total incident solar radiation on facade and monthly averaged outside dry-bulb air temperature.

3.3. Sensitivity analysis

Building physics problems are complex. The model used in this study to simulate the integrated building performance is neither linear nor monotonic. So the variance-based method is preferred because variance-based methods can cope with non-linear and non-monotonic models and appreciate the interaction effects among input factors. One of the most efficient variance-based measures available is the extended FAST method. This measure features a rapid convergence and can compute the first order sensitivity indices (S_i) and total order indices (S_{Ti}) using the same sample set. These sensitivity indices are defined on the expected value (E) and the variance (V) of an output $Y(X_1, X_2, \ldots, X_k)$ as:

$$S_i = \frac{V[E(Y|X_i)]}{V(Y)} \tag{8}$$

$$S_{Ti} = \frac{E[V(Y|X_{\sim i})]}{V(Y)} = 1 - \frac{V[E(Y|X_{\sim i})]}{V(Y)} \tag{9}$$

where S_i represents the main effect contribution of the ith input factor to the variance of the output. It has a value always between 0 and 1. The difference between S_i and S_{Ti} is a measure of how much the ith input factor is involved in interactions with any other input factors. If a factor is non-influential, it will have a very small value of S_{Ti} and can be fixed at any value within its distribution. This is beneficial to simplify the model and enable further studies such as optimization analysis. For fully additive models, the sum of S_i is equal to 1 and less than 1 otherwise. The sum of all S_{Ti} is always greater than 1 (equal to 1 for perfectly additive models).

In this study, the variance-based sensitivity analysis is performed in extended FAST implementation. The classic FAST method was introduced in the 1970s [4] to compute only the first order sensitivity indices. Later, Saltelli et al. [31] improved it to extended FAST method which is also capable of computing higher order and total order indices. The main principle of the FAST method is to relate the probability distribution function of each input parameter to a search function characterized with an integer frequency. By doing this, the k-dimensional integral in X (to calculate the expectation and variance of the output Y) is converted into a one-dimensional integral in s with the transformation function G_i for each input:

$$X_i = G_i(\sin \omega_i s) \tag{10}$$

where $s \in (-\pi, \pi)$ is a scalar variable and ω_i is the characteristic integer angular frequency for x_i. A recommended transformation function G_i is [31]:

$$X_i = \frac{1}{2} + \frac{1}{\pi}\arcsin(\sin(\omega_i s)) \tag{11}$$

Thus, for properly chosen ω_i, the model output can be expanded with a Fourier series as [42]:

$$Y = f(X_1, X_2, \ldots X_k) = f(s) = A_0 + \sum_{j=1}^{\infty}(A_j \cos(js) + B_j \sin(js)) \tag{12}$$

where $A_0 = (1/2\pi)\int_{-\pi}^{\pi} f(s)\mathrm{d}s$ is the approximation of the expectation of output Y, and the Fourier coefficients are: $A_j = (1/2\pi)\int_{-\pi}^{\pi} f(s)\cos(js)\mathrm{d}s$, $B_j = (1/2\pi)\int_{-\pi}^{\pi} f(s)\sin(js)\mathrm{d}s$ for $j = 1,2, \ldots, k$. The variance of Y can be approximated by Eq. (13).

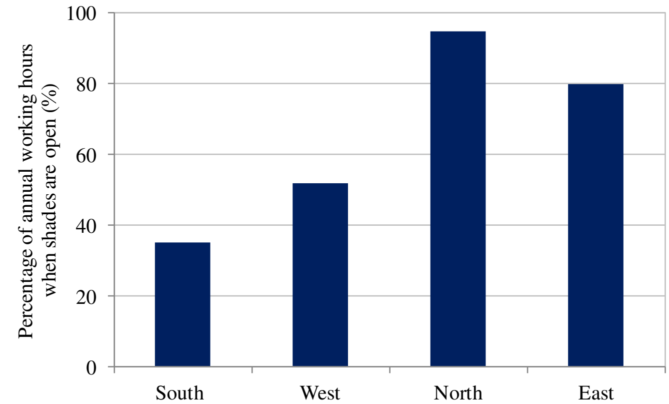

Fig. 4. Percentage of annual time (working hours) during which automated shades remain open for the four major orientations.

$$V(Y) = \frac{1}{2\pi}\int_{-\pi}^{\pi} f^2(s)\mathrm{d}s - [E(Y)]^2 \approx \sum_{j=-\infty}^{\infty}\left(A_j^2 + B_j^2\right) - \left(A_0^2 + B_0^2\right) \approx 2\sum_{j=1}^{\infty}\left(A_j^2 + B_j^2\right) \tag{13}$$

The minimum sample size [31] for FAST method to compute the sensitivity indices is:

$$n = 2M\omega_{max} + 1 \tag{14}$$

where M is the maximum harmonic considered (usually taken to be 4 or 6 [4] and ω_{max} is the maximum frequency amongst the set of ω_i. More details about the FAST can be found in [32–34]. This study uses SimLab 2.2 [16] to generate sample set and compute the sensitivity indices.

4. Application of uncertainty and sensitivity analysis in a case study

The uncertainty and sensitivity analysis were applied for a typical private office space located in Philadelphia using the described simulation model. The office has one exterior facade and is with automated interior roller shades. Weather information for Philadelphia is illustrated in Fig. 3 as the variation of monthly total incident solar radiation on facade and monthly averaged outside air temperature using TMY3 weather data [26] and the Perez model [28].

Table 1
Description and range of the studied design variables.

Design variable	Symbol	Unit	Distribution	Range
Window size	wwr (wfr[a])	–	Uniform	[0.1, 0.9]
Space aspect ratio	ar	–	Uniform	[0.6, 1.5]
Shade transmittance	τs	–	Uniform	[0, 0.25]
Front side shade absorptance	αf	–	Uniform	[0.05, 0.7]
Back side shade absorptance	αb	–	Uniform	[0.05, 0.7]
Facade insulation R-value	ins	m^2 K/W	Uniform	[1.2, 2.8]
Glazing type	g	–	Discrete	1, 2, … 6

[a] In the following sections, results are presented to wfr. Because the area of the exterior facade is changing with the variation of ar, distribution and range of wwr is given and used to calculate the corresponding wfr.

Table 2
Properties of selected glazing systems at normal incidence angle.

Glazing type	Visible transmittance	Solar transmittance	First pane absorptance	Second pane absorptance	Coating emissivity	*U*-value (W/m^2 K)
g-1	0.786	0.607	0.167	0.113	–	2.689
g-2	0.717	0.473	0.337	0.086	0.2	1.907
g-3	0.647	0.307	0.396	0.031	0.04	1.667
g-4	0.482	0.313	0.437	0.051	0.11	1.793
g-5	0.384	0.19	0.53	0.021	0.062	1.705
g-6	0.361	0.185	0.327	0.023	0.043	1.668

The space has a floor area of 16 m^2 and a height of 3 m. For office spaces, it is generally preferred that direct sunlight is not allowed to enter the space. Therefore, the interior roller shade is controlled to automatically close when incident beam radiation on the facade is higher than 20 W/m^2 during office hours (9 a.m.–5 p.m.) – and they are kept closed during non-office hours for privacy. The shading schedules during working hours throughout the year can be expressed as the percentage of time during which shades remain open (Fig. 4). The lighting system in the space is continuously dimmable to compensate daylighting illuminance so as to reach the illuminance requirement of 500 lux on work plane (0.8 m above floor). The lighting system has a power density of 10 W/m^2 with 30% of the released heat convected to air directly [1]. The other 70% of the heat released by lights goes to all surfaces as internal radiative heat gains according to their respective area-absorptance weights. The interior surface reflectances of the floor, ceiling and walls are 45%, 80% and 50% respectively. The exterior facade is composed of a brick layer (thickness: 10 cm, solar absorptance of 60%), insulation and gypsum board. Occupant density in the space is 0.11 p/m^2, and sensible heat gain form each occupant is 76 W. Load factor of the office space is 5.4 W/m^2 during office hours [1]. Heating and cooling are always available throughout the year. The heating set point during office hours is 22 °C and 18 °C otherwise. The cooling set point during office hours is 24 °C and 26 °C otherwise. The heating system consumes natural gas with an overall system efficiency of 80%. The cooling system consumes electricity with an average COP of 3.5. These values are typical and were used to convert thermal loads to source energy use (source-site ratios are 3.34 for electricity and 1.047 for natural gas).

Daylighting and energy performances are both investigated in the uncertainty and sensitivity analysis. Evaluated performance metrics include useful daylight illuminance between 500 and 2000 lux (UDI), annual lighting, heating and cooling demand per unit floor area and annual source energy consumption per unit floor area. A detailed explanation of the selection of performance metrics can be found in a previous study [35].

4.1. Selection of design factors

There are many design parameters that affect the perimeter building performance, such as glazing size and properties, shading properties and control, lighting system control, room aspect ratio, facade orientation and facade insulation condition. It is obvious that facade orientation has great impact on building performance [25,35]. However, the orientation is not a factor that can be fully controlled. So the analysis is performed for each main orientation in this study. From the study of Heiselberg et al. [12], lighting control is also an important factor influencing building primary energy consumption. Besides, the benefits of daylighting are mostly exploited when the lighting system is actively controlled. Therefore, this analysis is under the condition of a continuously dimmable lighting system. Considered design parameters include: window size represented with window-to-wall ratio (wwr) or window-to-floor ratio (wfr); space aspect ratio (ar, room length to room depth); roller shade transmittance (τs); front side roller shade absorptance (αf); back side roller shade absorptance (αb); facade insulation *R*-value (ins); and glazing type (*g*). For some factors, uniform distribution is a suitable representation of their possibility density function and range, since it is reasonable to assume that all the design values have equal selection possibility. On the other hand, there are some factors that do not have continuous values but are discrete variables. Considering glazing properties as an example, the values of visible transmittance, solar transmittance, solar absorptance of each glass pane and glazing system conductivity are tightly related. Taking each of the properties as a factor and assigning them with a separate distribution is not a practical solution to the analysis. For this reason, these properties are grouped as one factor – glazing type–- in this study. Table 1 summarizes the range and distribution of each design variable selected for the analysis of the perimeter private office.

In Table 1, facade insulation *R*-value is referring to benchmark building models [5] and related standards. For the selection of glazing type, according to the properties of double glazing listed in ASHRAE Handbook [1]; six kinds of glazing are selected from WINDOW 6 [45] to cover a range of glazing properties. The angular properties are used in the integrated building model for detailed and accurate simulation. Their properties at normal incidence angle are listed in Table 2.

4.2. Results and discussion

4.2.1. Uncertainty analysis

Based on the seven selected design parameters, the MC-LHS method is employed to obtain the mean values, standard deviations and variation coefficients of the useful daylight illuminance (500–2000 lux), lighting, heating and cooling demand and source

Table 3
Mean, standard deviation and coefficient of variation of UDI, lighting, heating and cooling demand of the studied private office for the four main orientations.

Orientation	UDI (%)			Lighting demand (kWh/m^2 year)			Heating demand (kWh/m^2 year)			Cooling demand (kWh/m^2 year)		
	μ	σ	ν (%)	μ	σ	ν (%)	μ	σ	ν (%)	μ	σ	ν (%)
South	37.9	22.3	58.7	10.2	6.3	62.1	22.6	5	22.2	41.9	13.4	32
North	52	21	40.3	5.7	3.8	68	31.5	6.5	20.6	31.7	9.4	29.7
East	47	18.4	39.2	7.1	4.3	59.9	28.2	5.9	20.8	39.4	13.3	33.8
West	43.7	20.2	46.3	8.4	5.3	63.2	27.9	6	21.5	43.1	14.5	33.8

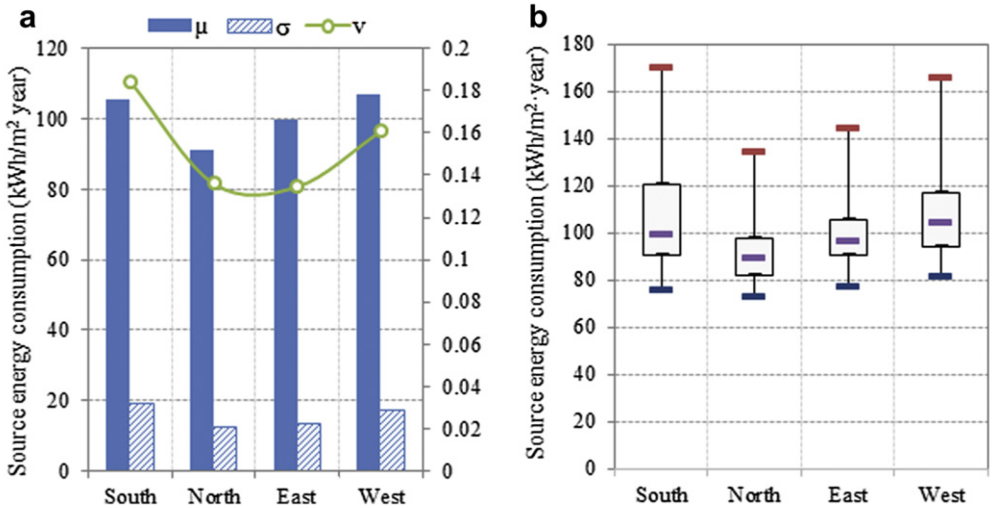

Fig. 5. (a) Mean, standard deviation and coefficient of variation of source energy consumption and (b) box plot of source energy consumption showing maximum, upper quartile, median, lower quartile and minimum values for four main orientations.

energy consumption for each orientation. A large enough sample with 140 runs is generated and executed to obtain their values. Table 3 shows these information for the first three building performance.

As shown in Table 3, lighting demand has the highest coefficient of variation up to over 60%, followed by UDI (40%–60%), cooling demand (around 30%), and heating demand (20%). The high values of coefficient of variation highlight large dispersions of the outputs, indicating that decisions should be made very carefully in the design stage to ensure that the various building performance indices remain in the preferred range. Comparing the four orientations, south and west show higher variation coefficient in terms of UDI while north and east show lower and similar variation coefficient. For lighting, heating and cooling demand, the four main

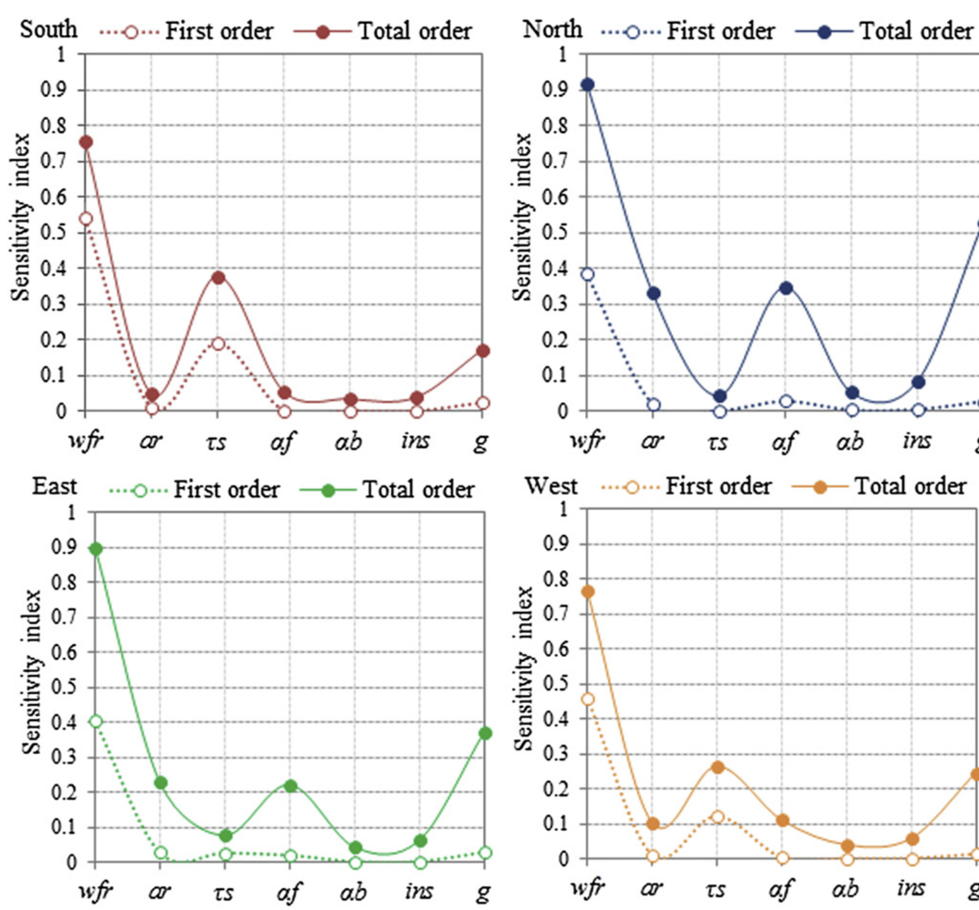

Fig. 6. First order and total order sensitivity indices – UDI (500–2000 lux).

orientations have similar values of variation coefficient. Compared to the above, source energy consumption has a lower coefficient of variation. Fig. 5 illustrates the statistical characteristics of annual source energy consumption per unit floor area for the four main orientations.

The coefficients of variation for source energy consumption are lower than 20% for all four main orientations. South and west facades show similar source energy consumption in terms of the median, maximum and minimum values. The variation coefficient for south is higher than west since the middle 50 quartiles for south covers a wider range. North and west facades show similar coefficient of variation while north requires less source energy. The large dispersion of all evaluated building performance calls for a further analysis to identify the most influential factors. Because the different orientations show different uncertainty characteristics, the sensitivity analysis needs to be performed for every main orientation.

4.2.2. Sensitivity analysis

Using the extended FAST method, a sample set with length equal to 460 data is generated and executed. The first and total order sensitivity indices are computed for all the studied building performances and orientations.

4.2.2.1. UDI and lighting demand. Fig. 6 shows the sensitivity indices of the seven studied design factors in terms of UDI performance for the four main orientations. Window-to-floor ratio has a dominating influence on UDI performance with high values for both first order and total order indices. For south and west, shade transmittance also has significant influence on UDI performance indicated by the first order indices. But for north and east facades, first order indices show that shade properties almost have no impact on UDI. This can be explained by the longer periods with open shades for north and east than south and west (Fig. 4). Glazing type does not have a significant impact on UDI for all orientations as seen from its first order indices. This is reasonable since for south and west, the effective transmittance of glazing-shade system mainly depends on shading transmittance; and for north and east, transmitted daylight is high enough (sometimes too high) for most of the office hours. However, when total order indices are computed, they show that glazing type is an important and influential factor for all orientations. It is reasonable to expect that the impact of glazing type is mostly involved in interactions with shading properties. For north and east, the front side shade absorptance (or reflectance since the sum of properties is equal to 1) shows much higher total order indices than first order indices. This is somewhat out of expectation and difficult to explain since

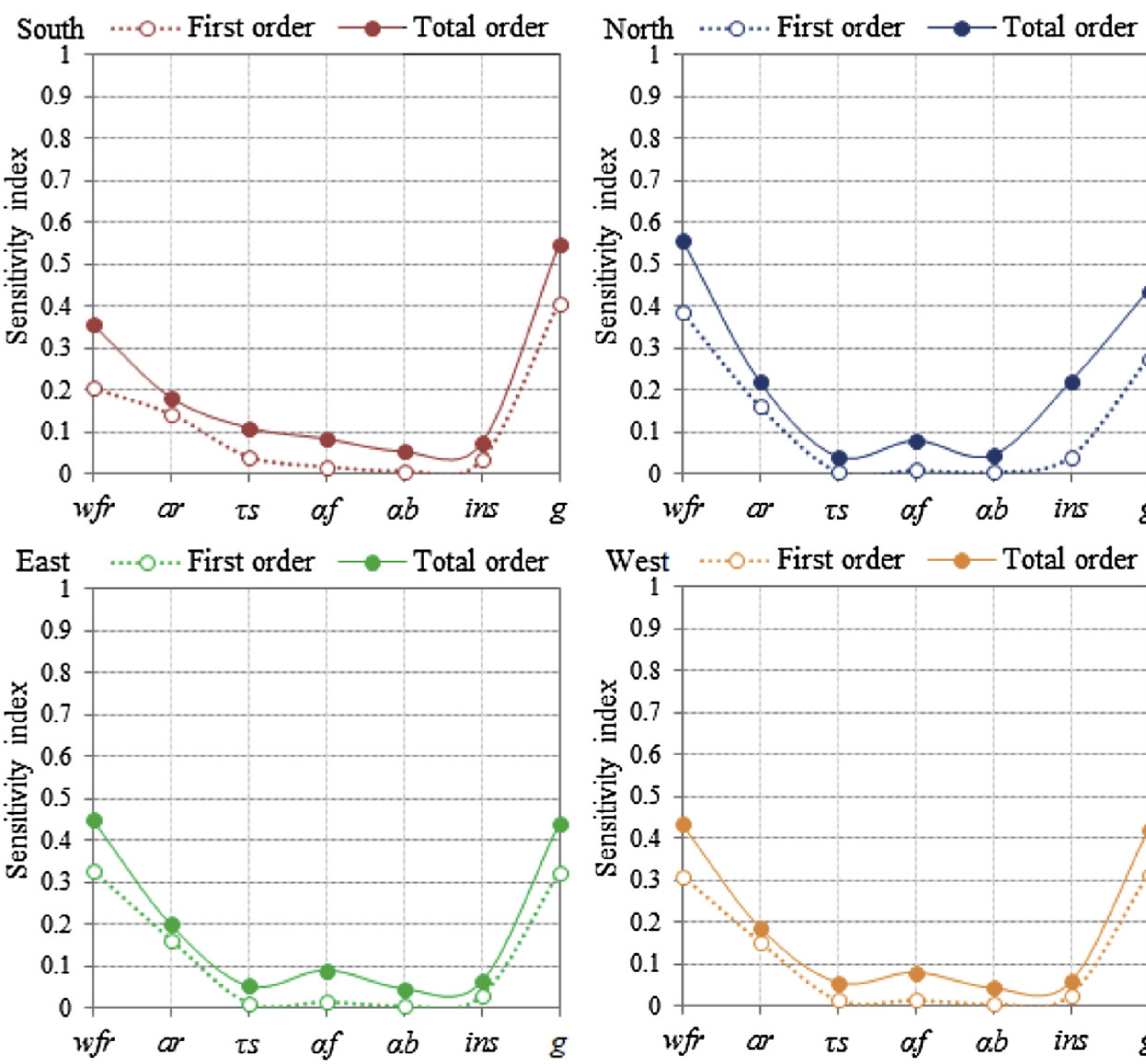

Fig. 7. First order and total order sensitivity indices – heating demand (kWh/m^2 year).

the definition of UDI is an illuminance range (between 500 and 2000 lux). Low illuminance (lower than 500 lux) and high illuminance (higher than 2000 lux) will both result in low UDI values.

Generally, the sensitivity indices of the studied factors on lighting demand show very similar characteristics as on UDI. This is reasonable since the lighting system is controlled based on available daylight.

4.2.2.2. Heating demand and cooling demand. Figs. 7 and 8 show the sensitivity indices of the seven studied design factors in terms of heating and cooling demand respectively. Window-to-floor ratio and glazing type dominate the variation of both heating demand and cooling demand. For heating demand, space aspect ratio is the third important factor for south, east and west, while space aspect ratio and facade insulation *R*-value are the two almost equally third important factors for north-facing offices. It may be confusing that the facade insulation condition is not as important as expected. However, this can be explained by the studied case of a small private office with only one exterior facade where solar gains play a major role. This solar heat gain alleviates heating needs and deteriorates cooling needs. In this sense, shade transmittance should have important impact on heating demand and cooling demand. This is true for south but not for other orientations. A possible reason is that the incident solar radiation on south facade is high during the heating period, but much lower for other orientations (Fig. 3); and during the cooling period it is attributed to the longer sunshine time for south than other orientations during office hours (note that the set points are different for office hours and non-office hours). Internal gains which are inevitable in office spaces also play an important role.

4.2.2.3. Source energy consumption. When it comes to source energy consumption, the results are quite different. Although source energy consumption is calculated from energy consumption for lighting, heating and cooling, the relationship may not be applied to sensitivity indices. First, the energy consumption for lighting, heating and cooling is not independent – there is a complicated relationship between them. For example, if lighting needs increase, the cooling needs may also increase and the heating needs may decrease – this is considered in the transient building simulation model used.

Fig. 9 shows the sensitivity indices of the seven studied design factors in terms of source energy consumption for four main orientations. Fig. 9 shows that window-to-floor ratio and glazing type are very important factors for all the four main orientations. For south and west facades, another important factor is the shade transmittance. For north facades, space aspect ratio and insulation conditions are also significant. Front side shade absorptance is the third most important factor for east-facing rooms.

4.2.3. *Global effect of inputs on source energy consumption variation*

After obtaining the importance indices of the studied factors, it is beneficial to estimate the variation of the source energy consumption to the inputs. The scatter plot is a suitable way to reveal the relationship between the model output and its inputs. Fig. 10 shows the scatter plot of source energy consumption to some important factors for south and north-facing facades, where the relationship between source energy consumption and shown design parameters are well revealed. Fig. 11 presents an interesting case: the scatter plot of source energy consumption with window-to-floor ratio for east-facing offices. Such results are observed when

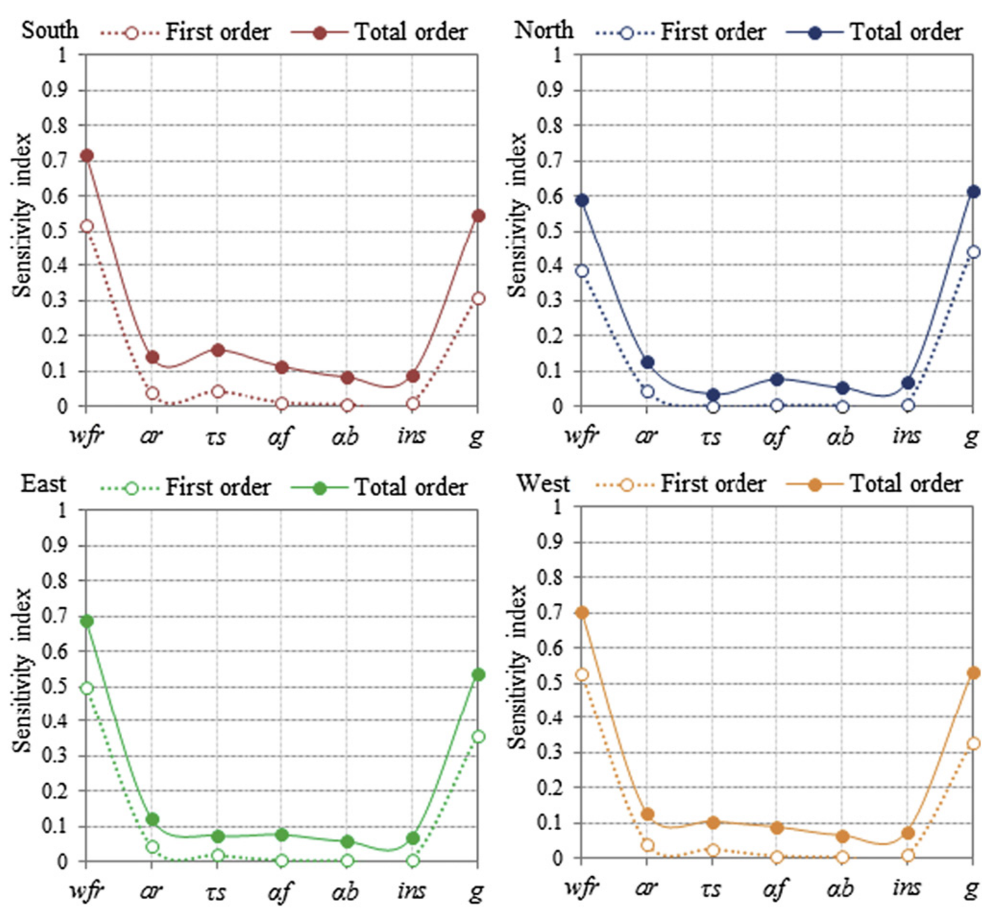

Fig. 8. First order and total order sensitivity indices – cooling demand (kWh/m^2 year).

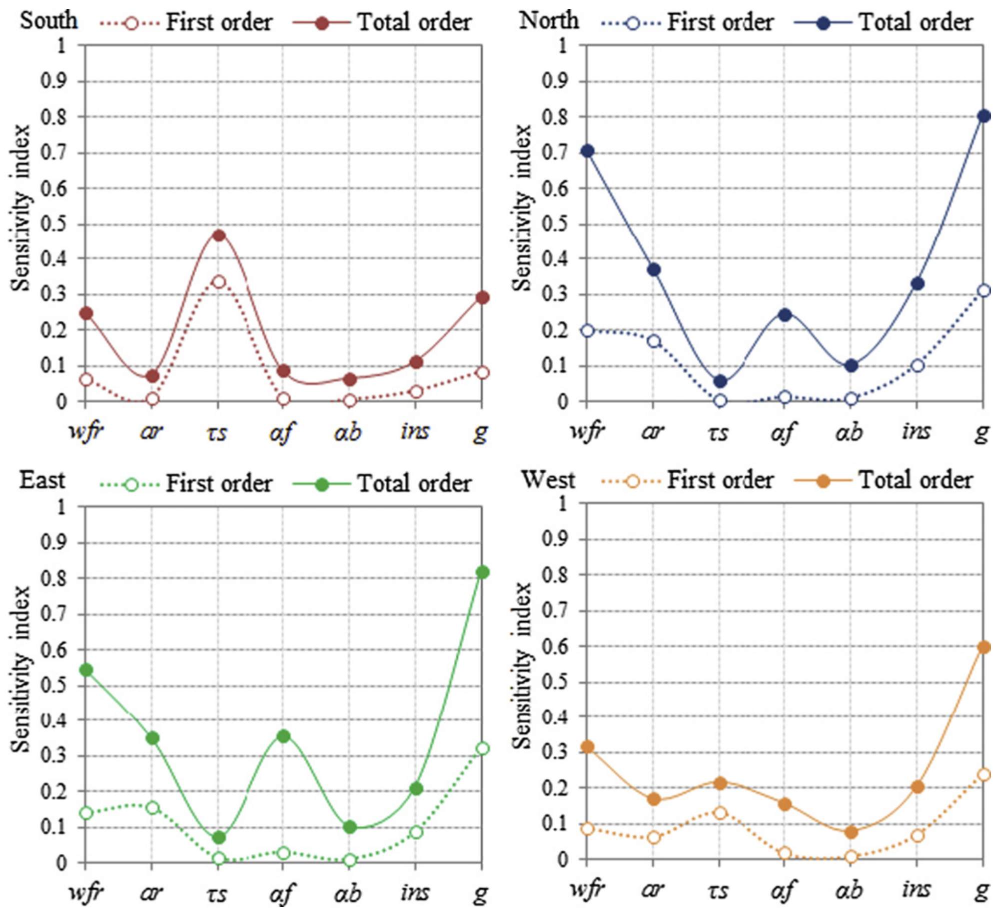

Fig. 9. First order and total order sensitivity indices – source energy consumption (kWh/m^2 year).

there is a strong relationship between an input of great significance and the output and are particularly useful for design and optimization purposes.

For factors with discrete distribution like the glazing type, the box plot is preferred to illustrate the results (Fig. 12). It can be seen that Glazing-3 performs better in terms of space source energy consumption. This type of glazing has high visible transmittance but comparatively low solar transmittance as well as low coating emissivity (low U-value) and low solar absorptance. Because these glazing properties are related with each other and are not continuously available in the market, it is more reasonable to compare them as a group (one glazing type) and pick the best performing one.

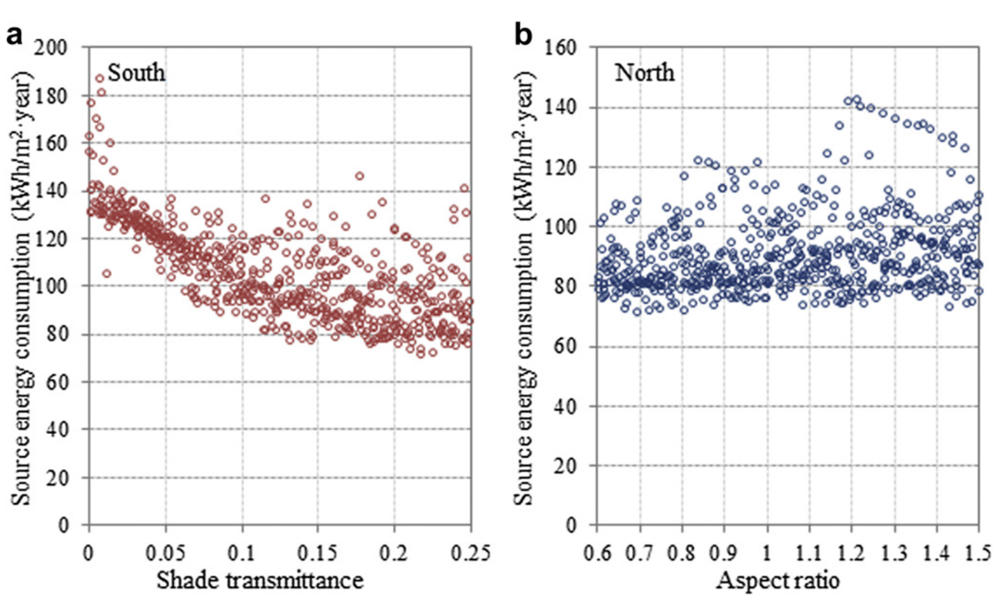

Fig. 10. Variation of source energy consumption with (a) shade transmittance for south-facing offices and (b) space aspect ratio for north-facing offices.

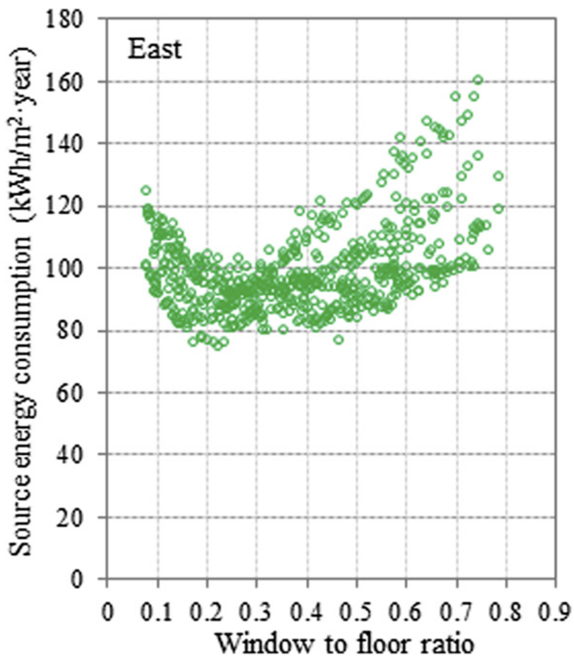

Fig. 11. Variation of source energy consumption with window-to-floor ratio for east-facing offices.

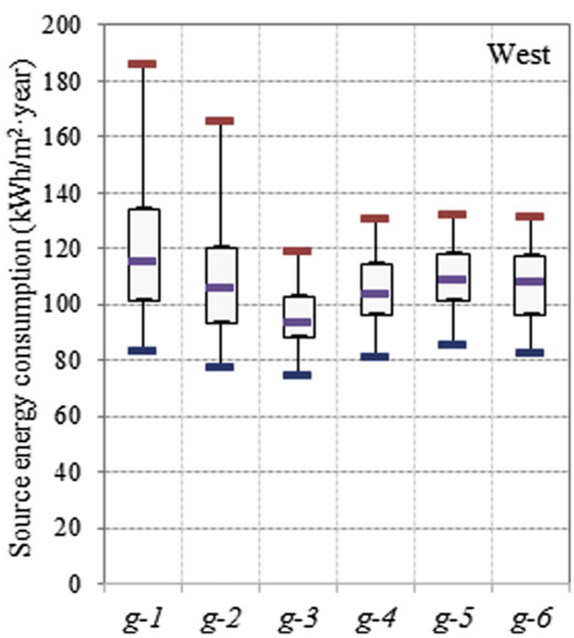

Fig. 12. Box plot of source energy consumption to different glazing systems for west-facing offices showing maximum, upper quartile, median, lower quartile and minimum values for four main orientations.

5. Conclusion

This paper presented a sensitivity analysis of five building performance metrics to seven selected design parameters. The purpose was to identify the more important factors with respect to building thermal and lighting energy performance so as to facilitate decision making in building design stage and simplify further study such as optimization analysis.

An integrated transient daylighting and energy model (with annual runs) developed in a previous study with two improvements was employed to simulate the building performance. A perimeter private office in Philadelphia was used as a case study. The studied building performances included UDI (500–2000 lux), lighting, heating and cooling demand and source energy consumption. Considering the possible influential factors, seven design parameters are selected: window-to-floor ratio, shading transmittance, shading front and back reflectance, space aspect ratio, insulation thermal resistance and glazing type. Glazing properties, such as visible transmittance, solar transmittance and *U*-value, are not continuously available from market and more importantly, they are not independent with each other, therefore they were grouped as one factor – glazing type- in the analysis.

An uncertainty analysis was performed first to evaluate the necessity for further sensitivity analysis. The analysis is based on MC-LHS method with 140 runs. Significant dispersion of the building performance is evaluated, indicating that the studied factors should be carefully designed to achieve certain design targets. A sensitivity analysis was then performed: based on the characteristics of the building model, a variance-based method was selected. Using the extended FAST module in SimLab 2.2, a sample set with length of 460 data was generated and the first and total order sensitivity indices were computed for each studied design factor. The following conclusions are drawn from the results:

(i) The uncertainty analysis shows high dispersions of all investigated performance metrics (13–68%), indicating that decisions should be made very carefully in the design stage to ensure that the various building performance indices remain in the preferred range.
(ii) For all evaluated performance metrics, window-to-floor ratio and glazing type have a significant impact.
(iii) For useful daylight illuminance, window-to-floor ratio has a great influence with first order sensitivity index varies from 0.38 to 0.54 and total order sensitivity index varies from 0.75 to 0.91. The impact of glazing type is usually involved with other design parameters, showing low first order sensitivity index around 0.02 but high total sensitivity index varies from 0.17 to 0.53. For annual lighting demand, the impact is similar to that of useful daylight illuminance.
(iv) For annual heating demand, window-to-floor ratio makes a contribution varying from 0.2 to 0.39 (total indices vary from 0.35 to 0.56), and window type similarly varying from 0.27 to 0.41 (total indices varies from 0.42 to 0.55).
(v) For annual cooling demand, window-to-floor ratio shows high first order impact ranging from 0.39 to 0.53 with total impact around 0.7. The glazing type also shows significant impact with first order sensitivity index (0.31 to 0.44), and total sensitivity index around 0.55.
(vi) When it comes to annual source energy consumption, different orientations have their own slightly different import factors. For south facades, the most important factor is the shade transmittance (first order index: 0.34, total order index: 0.47), followed by glazing type (first order index: 0.08, total order index: 0.29) and window-to-floor ratio (first order index: 0.06, total index: 0.25). West facades have the same import factors in different order: glazing type (first order index: 0.24, total order index: 0.6), window-to-floor ratio (first order index: 0.09, total order index: 0.32) and shade transmittance (first order index: 0.18, total order index: 0.16). North and east facades have different important factors in the order of glazing type, window-to-floor ratio and front side shade absorptance.
(vii) For different orientations, the rank of factor importance changes slightly because of different outside conditions such

as incident solar radiation and the resulting different shading schedules and lighting operation.

The value of sensitivity indices strongly depends on the range of inputs. When the range changes, both the indices' value and importance rank may change. This paper was focused on a typical perimeter private office with one external facade. The interior roller shade and lighting system were controlled with certain algorithms, so the results may not applicable to other spaces with different conditions. Finally, some of the studied parameters will also have a significant impact on thermal and visual comfort, which should also be investigated in a future study.

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